THEORY AND OPERATION OF THE "AERO-THERMOPREX"

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" AERO - THERMOPREX "

by

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Naval Engineer

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Cambridge, Massachusetts
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Professor J. S. Newell
Secretary of the Faculty
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Cambridge, Massachusetts

Dear Sir:

In accordance with the requirements for the Degree of Naval Engineer, we submit herewith a thesis entitled "Theory and Operation of the 'Aero - Thermoprex' ".

Respectfully,

FOREWORD

An investigation of the "Aero-Thermoprex" was conducted as a joint project by Lieutenants R. A. Hawkins, L. V. Mowell, O. A. Templeton, and J. R. Wish. Since the investigation covers many phases, the report has been divided into two sections. The first report, by Hawkins and Mowell, covers the design, construction and preliminary tests of the "Aero-Thermoprex", and includes the theoretical analysis for design, and a modified analysis for the apparatus constructed. The second report, by Templeton and Wish, covers the actual performance of the apparatus and a comparison with the theory to determine the possibilities of the "Aero-Thermoprex" as a machine.

ACKNOWLEDGEMENT

The authors wish to express their appreciation to Professor A. H. Shapiro for his valuable advice and assistance, and for the suggestions which originally inspired this investigation. The authors are grateful to the personnel of the U. S. Naval Engineering Experiment Station, Annapolis, Md., and the Boston Naval Shipyard and the Massachusetts Institute of Technology Gas Turbine Laboratory for their assistance with the experimental equipment. The authors also wish to express their appreciation to Lieutenant R. A. Hawkins and Lieutenant L. V. Mowell for their assistance with the experimental work and their suggestions in the preparation of this thesis.

TABLE OF CONTENTS

NOMENCLATURE

Symbol	Quantity Represented
A	Cross-sectional area of the gas stream
D	Hydraulic Diameter
f	Friction Coefficient
M	Mach Number
P	Pressure
T	Absolute Temperature
W	Weight rate of flow
x or L	Distance along the duct

Subscripts

a	Gas
f	Gas conditions at the outlet from the evaporation section
i	Gas conditions at the inlet to the evaporation section
w	Water (liquid or vapor)
1	Gas conditions at the inlet to the nozzle
2	Gas conditions at the outlet receiver
01, etc.	Isentropic stagnation conditions at section 1, etc.

I. SUMMARY

A theoretical one-dimensional analysis of a supersonic gas stream shows that a stagnation pressure rise may be attained under certain conditions, by a constant temperature evaporation of water in the stream. The "Aero-Thermoprex" is a gas pumping device which operates on this principle. The purpose of this investigation is to determine experimentally the operating characteristics of the "Aero-Thermoprex", and to compare its operation with the theoretical analysis. It is particularly desirable to determine the possibilities of the "Aero-Thermoprex" as a gas pump because of the need for alternatives to conventional compressors for large supersonic wind tunnels.

Experiments were conducted on the apparatus, which consists of a supersonic nozzle to accelerate a heated gas stream followed by an evaporation and diffusion section to produce a stagnation pressure rise in the gas stream. The optimum operating conditions were determined for this apparatus and the results compared with the theoretical analysis to establish the possibilities of the "Aero-Thermoprex".

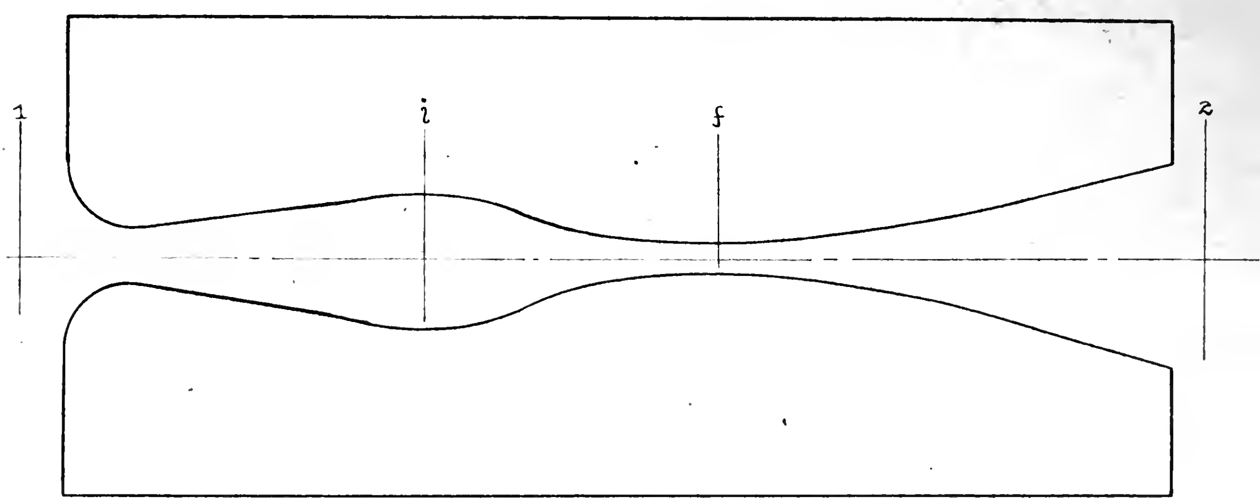
Experimental results show that the evaporation section of the "Aero-Thermoprex" produces a final pressure <u>28.5%</u> greater than the pressure attainable without water injection, although the pressure rise is not great enough to produce a net stagnation pressure ratio greater than unity, and no pumping action is attained. The experimental results partially substantiate a modified theoretical analysis, which shows that on an apparatus of experimental size it is not possible to obtain a stagnation pressure rise because of frictional effects and incomplete evaporation.

The stagnation pressure ratio obtained experimentally is less than that predicted by the modified one-dimensional theory. In converging the supersonic stream in the evaporation section, oblique shocks and turbulent flow occur, causing losses which were not accounted for in one-dimensional theory. The performance of experimental apparatus can be improved by incorporating well designed supersonic and subsonic diffusers and incorporating a better water injection and evaporation system.

On a full size apparatus, a net stagnation pressure rise is uncertain, although the operation would be much improved. The water injection and evaporation and the supersonic diffusion could be improved, while the friction losses would be decreased. If a net stagnation pressure rise is not obtained, the "Aero-Thermoprex" is still useful, for it can reduce materially the compressor power needed to drive supersonic wind tunnels. If a net stagnation pressure rise is achieved, the "Aero-Thermoprex" can become a supersonic wind tunnel which requires no compressor.

II. INTRODUCTION

The "Aero-Thermoprex" is a gas pumping device which would raise the stagnation pressure of a supersonic gas stream without the use of mechanical work by evaporation of water in the stream. This scheme was suggested by Shapiro and Hawthorne (1) and a theoretical one-dimensional analysis was made by Shapiro and Wadleigh (2). Using the method of analysis suggested by the above works, Hawkins and Mowell (3) have selected a design point to give the optimum stagnation pressure rise within practical limits for a constant temperature process, and have constructed an "Aero-Thermoprex". This investigation is a sequel to the work of Hawkins and Mowell, who present the one-dimensional theoretical basis of the "Aero-Thermoprex", and it is intended that this investigation be read after the work of Hawkins and Mowell.



The apparatus (see illustration) was designed for an inlet stagnation

temperature (T_{01}) of 1500 deg. FA, an inlet stagnation pressure (P_{01}) of 14.7 psia, a Mach Number of 2.5, and a theoretical water injection rate (W_w/W_a) for complete evaporation of 0.14 for a final Mach Number in the evaporation section of 1.25. The one-dimensional analysis without friction (counterbalancing assumptions of $f = y = o$) and with instantaneous evaporation predicts a stagnation pressure ratio P_{02}/P_{01} of 1.6. However, Hawkins and Mowell show that the small size of this apparatus, made necessary by laboratory facilities, invalidates the assumptions of zero friction factor (i.e., f is greater than y) and instantaneous evaporation. They introduce a reasonable friction factor, 4f dx/D of 0.009, and show that a stagnation pressure ratio P_{02}/P_{01} of 1.1 is still possible if evaporation is complete. They have shown the evaporation in this apparatus should be between 50% and 100% complete. Using the same friction factor, 4f dx/D of 0.009, they have made calculations for injection of excess water to maintain constant temperature with 75% and 50% evaporation. These calculations show a stagnation pressure ratio less than unity for both, and for 50% evaporation, the final stagnation pressure is less than that calculated for no water injection at all.

The primary object of this investigation is to determine the optimum operating conditions of this "Aero-Thermoprex" and to interpret the results on the basis of the theoretical analysis. Secondary objects are the investigation of the effects of departure from one-dimensional flow and the investigation of the influence of absolute size on the results obtained. This latter investigation can be used for predicting the results obtainable in full size installations and the possible uses of the "Aero-Thermoprex".

It should be pointed out that constant temperature operation, for which the apparatus was designed, can be only approximated. Constant temperature operation would require infinitesimal injection steps in the evaporation section with instantaneous acceleration and evaporation. These requirements cannot be met in any actual apparatus.

The apparatus has sufficient flexibility so that tests can be conducted at various inlet temperatures and water injection rates other than the design values, and with appropriate area change in the evaporation section to accomodate the various conditions. The object in mind in carrying out the experimental tests was not to maintain a constant temperature process, but to obtain the best possible stagnation pressure ratio, P_{02}/P_{01}. The results are compared with theoretical curves for a constant temperature process, since the actual process approximates one of constant temperature. The complexity of the flow equations involved makes an analysis of the actual process too complicated to attempt.

III PROCEDURE

Experimental runs were made over a wide range of operating conditions to determine as fully as possible the operating characteristics of the "Aero-Thermoprex". The variable quantities included; inlet stagnation temperature, amount of water injected, types of injection and area change in the evaporation section. All tests were conducted with the design Mach Number of 2.5 at the inlet to the evaporation section. The data recorded were; inlet and outlet stagnation temperatures (T_{01}, T_{02}) inlet and outlet stagnation pressures (P_{01}, P_{02}), pressure tap readings, water injection rate, and handwheel settings for the evaporation section areas. (Original data is tabulated in appendix A.) The area change versus length in the evaporation section for various settings of the handwheels is shown in figure II. The different handwheel settings will henceforward be designated by the diffuser throat areas that they produce.

<u>The procedure for test runs without water injection was as follows:</u> (Numbers in parenthesis refer to schematic drawing, Fig. 1.)

a. The furnace (1) was lighted with the air-injector valve (16) just cracked, and the apparatus was allowed to warm up for several minutes.

b. With the diffuser throat area opened sufficiently by means of handwheels (10), the air ejector valve was opened wide and a supersonic flow started in the test section (4).

c. The inlet stagnation temperature T_{01} was adjusted to the desired value.

d. The exhaust cooling water system (14) was started.

e. With the diffuser throat area set at the desired test value, the back pressure was raised by closing the air-ejector valve until the shock was moved as close to the diffuser throat as possible without choking the flow.

f. Pressure tap (9) values, thermocouple (2) readings, and diffuser throat area settings (10) were recorded at this point.

g. The flow was then choked by closing the air-ejector valve still further, the value of P_{02} being noted at the instant of choking. Endeavor was made to keep the point at which complete test data were recorded as close to the choking point as possible.

h. The procedure above was repeated for the other desired values of the inlet stagnation temperature and diffuser throat area. The minimum diffuser throat area setting at which the supersonic flow would start was recorded, along with the minimum area to which the diffuser throat could be closed before the flow choked.

<u>The procedure for test runs with water injection was as follows:</u>

a. Steps (a) through (d) above were repeated, and the outer wall cooling spray (5) started.

b. The water injection pump (13) was started and the desired rate of flow obtained by regulating the pump by-pass valve. The desired type of water injection was used.

c. The diffuser throat area was decreased to the desired value if it were possible to do so without choking the flow.

d. The back pressure was raised by closing the air-ejector valve until the shock was moved as close to the diffuser throat as possible without choking the flow.

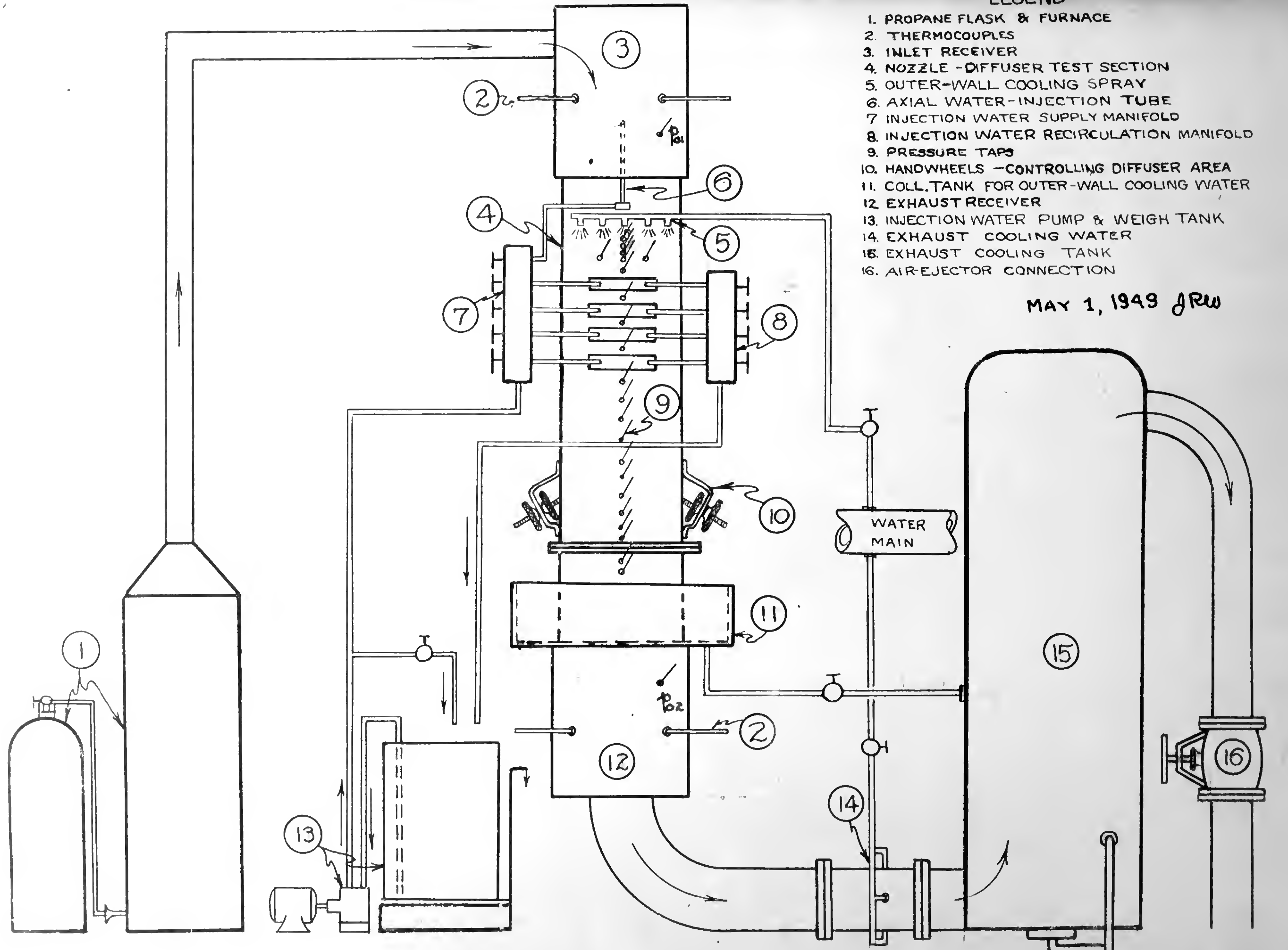
e. Readings of the pressure taps, thermocouples, diffuser throat area settings, and the amount of water injected were recorded.

f. The flow was choked and P_{02} was recorded at the instant of choking.

g. The above procedure was repeated with other values of T_{01}, amounts of water injection, and values of diffuser throat area. The minimum diffuser throat area was recorded for each water rate and type of injection.

Experimental data which was used for preparing curves showing the operation of the "Aero-Thermoprex" are recorded in Appendix A.

The performance for various test runs was compared with the predicted performance calculated for several theoretical cases. The best performance of the apparatus for runs without water injection and for runs with the optimum water rate were compared with the theoretical curves for 0%, 50%, 75%, and 100% evaporation; all with a friction factor, 4f dx/D, of 0.009.



LEGEND

1. PROPANE FLASK & FURNACE
2. THERMOCOUPLES
3. INLET RECEIVER
4. NOZZLE - DIFFUSER TEST SECTION
5. OUTER-WALL COOLING SPRAY
6. AXIAL WATER-INJECTION TUBE
7. INJECTION WATER SUPPLY MANIFOLD
8. INJECTION WATER RECIRCULATION MANIFOLD
9. PRESSURE TAPS
10. HANDWHEELS — CONTROLLING DIFFUSER AREA
11. COLL. TANK FOR OUTER-WALL COOLING WATER
12. EXHAUST RECEIVER
13. INJECTION WATER PUMP & WEIGH TANK
14. EXHAUST COOLING WATER
15. EXHAUST COOLING TANK
16. AIR-EJECTOR CONNECTION

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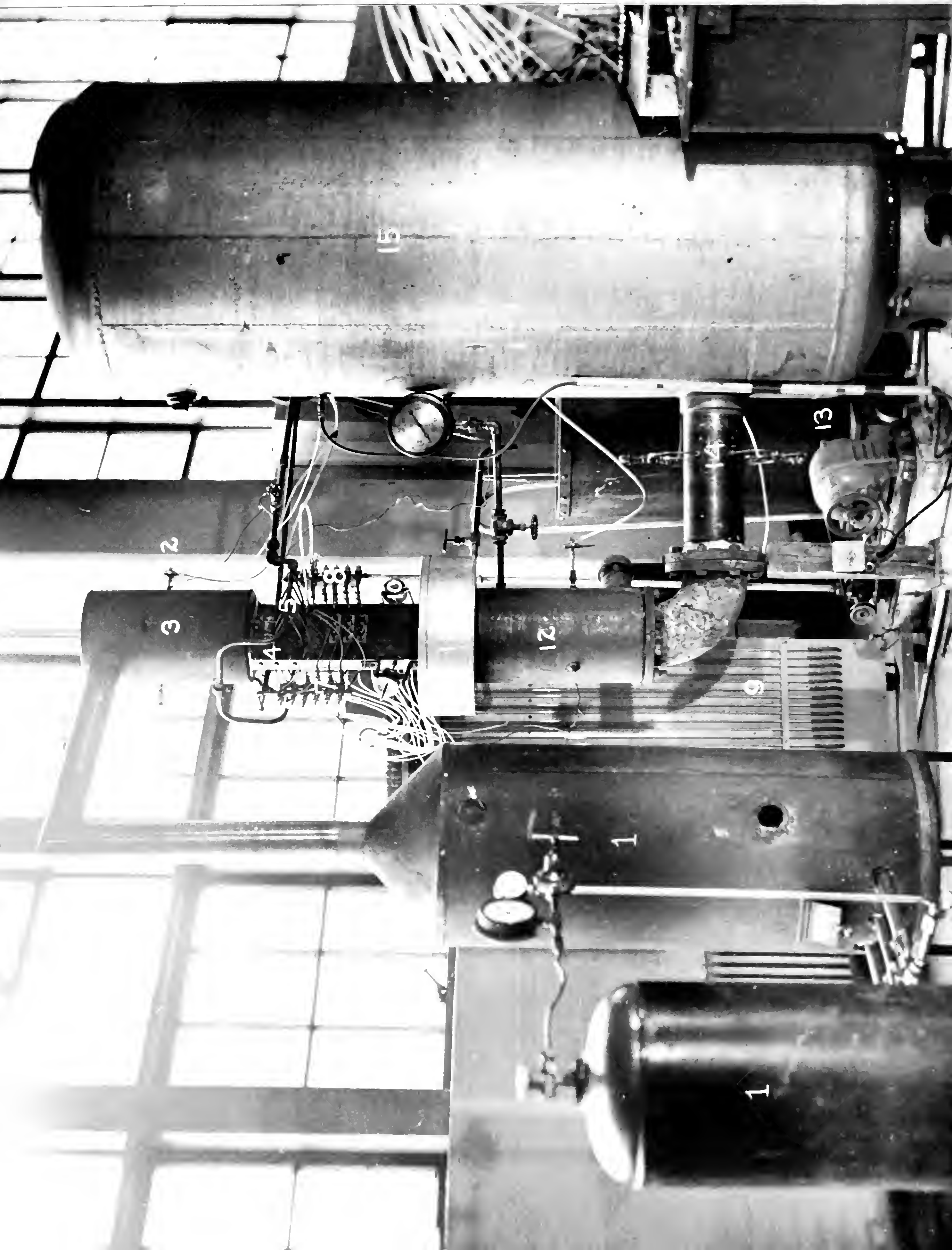
FIG. I

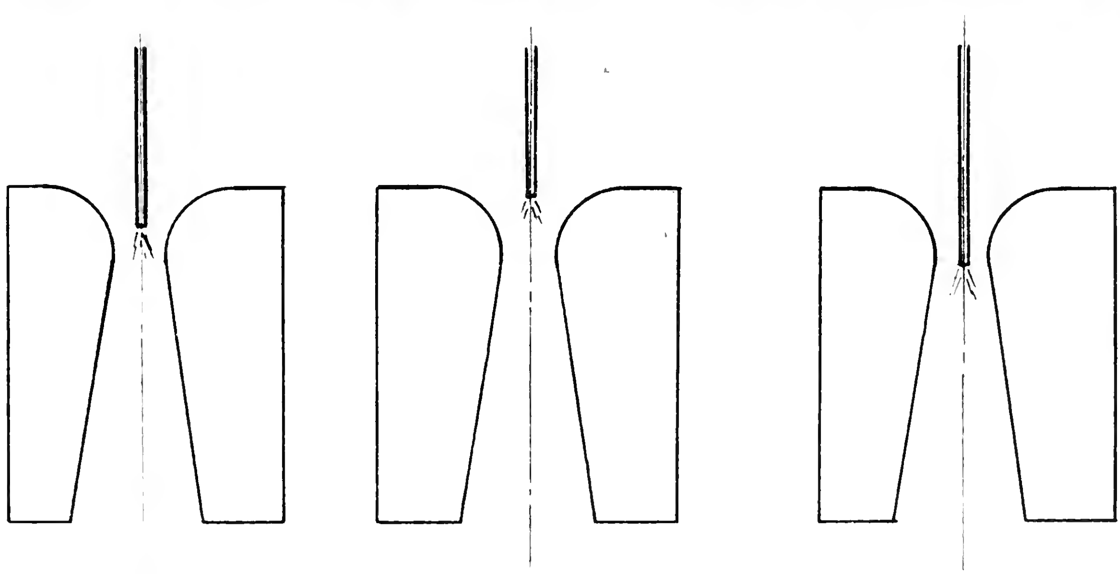
Fig. Ia. Photograph of apparatus. See legend Fig. I



IV RESULTS

Experimental data for the operation of the "Aero-Thermoprex" are presented in a manner which shows its optimum operating condition. The optimum operating condition is that condition for which the highest stagnation pressure ratio is obtained. The stagnation pressure ratio (P_{02}/P_{01}) is shown in figures III to VI, inclusive, for various conditions of operation. In figures VII to IX, the experimental results are compared with the results obtained from a modified theoretical one-dimensional analysis. No comparison of temperatures was made, since temperature measurement in the high speed gas stream was not possible. The results, both theoretical and actual, are obtained for an inlet Mach Number of 2.5.

Figure III shows the stagnation pressure ratio vs water injection rate for five different methods of water injection, and with an inlet stagnation temperature of 1500 deg. FA. Types A, B, and C consist of injection through an an axial tube, 0.05" i. d., located near the nozzle throat. In injection type A, the tube is located ½" before the throat,



TYPE "A" TYPE "B" TYPE "C"

for type B, it is 1" before the throat, and for type C, the tube is located at the throat. Tests for axial injection beyond the throat in the supersonic stream were unsuccessful due to the instability of the gas stream, and no data was obtained for this condition. Type E consists of injection through the sideplates of the evaporation section. This is a step-wise injection, which more closely resembles the mechanics of the theoretical analysis. Very little data was obtained with type E injection, because this method caused instability in the gas flow. No data was obtained for simultaneous injection through all side plates, for very strong shocks occurred with injection at the inlet to the evaporation section where the gas stream velocity was highest. Type D is a combination of the axial injection type A with the last two side blocks of type E.

Figure IV shows how the injected water was dispersed in the gas stream when axial injection was used. The photographs were taken of a Mach Number 2 Nozzle with optical flats for side plates. For all types of injection in this test, the water stream was broken up into an extremely fine fog by the shearing action of the high speed gas stream. Figure IVa shows the coverage of the gas stream with the injection tube before, near and after the nozzle throat and the injection at the injection at the theoretical design rate of 0.14 pounds of water per pound of air. Figure IV b shows the coverage of the gas stream with water injection rates above and below the design value. The effect of normal shock on the dispersion of the water is shown in figure IVc. The shock occurs at the section which shows the instantaneous complete coverage of the gas stream. No means were available for obtaining photographs of the side plate injection.

The effect of the inlet stagnation temperature on the stagnation pressure ratio is shown in Figure V. The curves show P_{02}/P_{01} vs evaporation section (diffuser) throat area for constant water injection rate. The water injection rate used at each temperature is approximately that for which the best stagnation pressure ratio could be attained.

In figure VI, the stagnation pressure ratio vs water injection rate is shown at the design inlet stagnation temperature of 1500 deg. FA for numerous experimental runs conducted with type A injection. Curves are plotted for constant values of diffuser throat area. The curves terminate at the limit lines which bound the region of possible operation. (The location of the limit lines is approximate.) The curves show that the highest stagnation pressure ratio, P_{02}/P_{01}, was reached with a water injection rate of 0.188 pounds of water per pound of air, and with the smallest diffuser throat area it was possible to obtain. If the evaporation were complete, the theoretical water injection rate required would be 0.14 pounds per pound of air for a final Mach Number of 1.25. For evaporation of 75% of the injected water, the rate required would be 0.187. These theoretical rates are shown on figure VI.

Figure VII shows a comparison of the theoretical curves obtained by one-dimensional analysis for a constant temperature evaporation process, and the actual curves for the process which yielded best results in the experimental runs. The theoretical and actual curves were obtained with design inlet conditions. The experimental run was made with water injection at the rate of 0.188 pounds of water per pound of air. The theoretical curves are plotted for water injection of 0.14, 0.187, and 0.28 for 100%, 75%, and 50% evaporation, respectively. Curves of A/A_1

and the corresponding P/P_{01} are plotted vs length, where L is zero at the inlet to the evaporation section, and L is 10 at the diffuser throat section, at which point the Mach Number is 1.25. (P_{0i} is taken equal to P_{01} for the actual curve, although they differ slightly. P_{0i} was not obtainable on the apparatus.) The length from 10 to 17 represents the length from the evaporation section at the diffuser throat to the outlet of the actual subsonic diffuser, where M is substantially zero. The theoretical curves were plotted with a Mach Number of 125 at the diffuser throat, since that was the minimum Mach Number obtainable at the diffuser throat for stable operation of the apparatus. The theoretical curves are continued with a normal shock and isentropic subsonic diffusion to zero Mach Number, using the Gas Tables.

Figure VIII shows a comparison of the theoretical and actual results without water injection. The theoretical one-dimensional calculation was made with the same friction factor as was used in the calculations with water injection. The curve A/A_1 vs length is the same for the theoretical and actual cases. The pressure curves P/P_{0i} vs length correspond to the above area curve. The experimental curves represent the best performance of the apparatus without water injection. The figure shows that at the diffuser throat, the actual pressure ratio, P/P_{0i} is 0.174, whereas the theory predicts a pressure ratio of 0.275. The ratio of $(P/P_{0i})_{actual}$ to $(P/P_{0i})_{theoretical}$ is 0.633.

In figure IX, the actual and theoretical pressures with no water injection are brought into agreement by reducing the theoretical pressure at the diffuser throat by a factor of 0.633. The pressures at the

outlet of the evaporation section for the theoretical curves with water injection are reduced by the same proportion, and compared with the diffuser throat pressure obtained experimentally. In figure IX, the experimental diffuser throat pressure agrees with the theoretical curve for 75% evaporation.

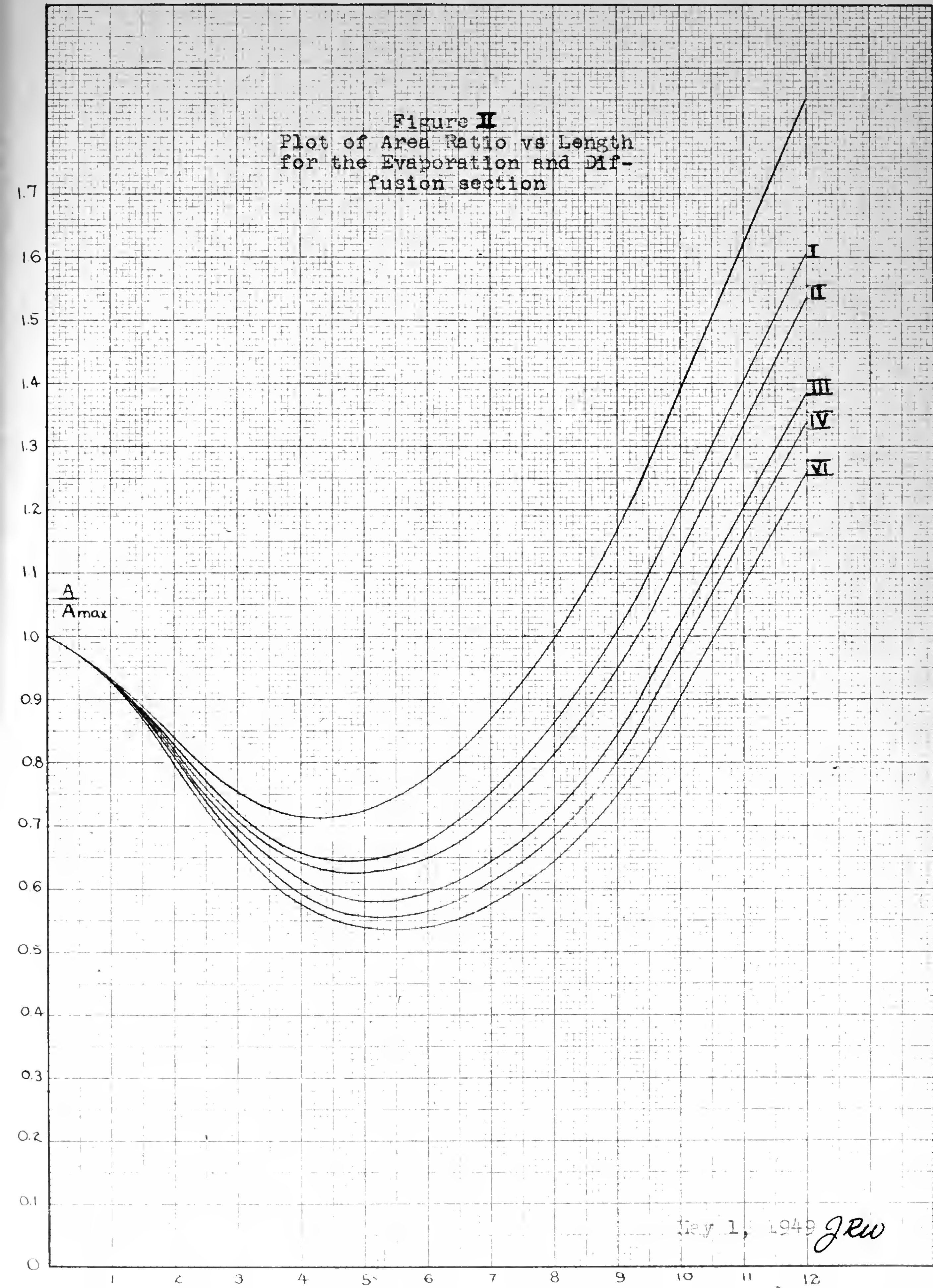


Figure II
Plot of Area Ratio vs Length
for the Evaporation and Diffusion section
I
II
III
IV
VI
A/Amax
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
8
9
10
11
12
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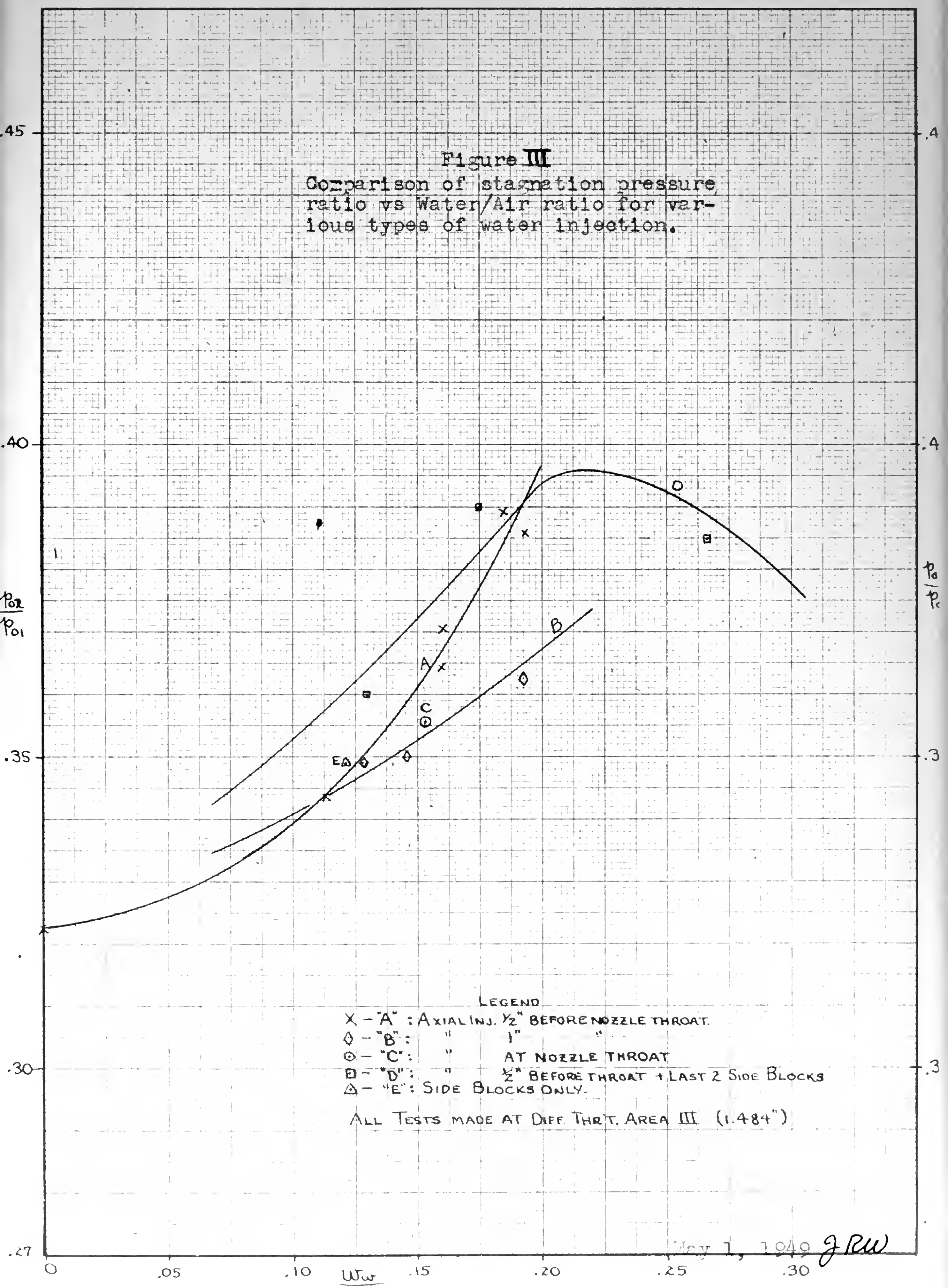
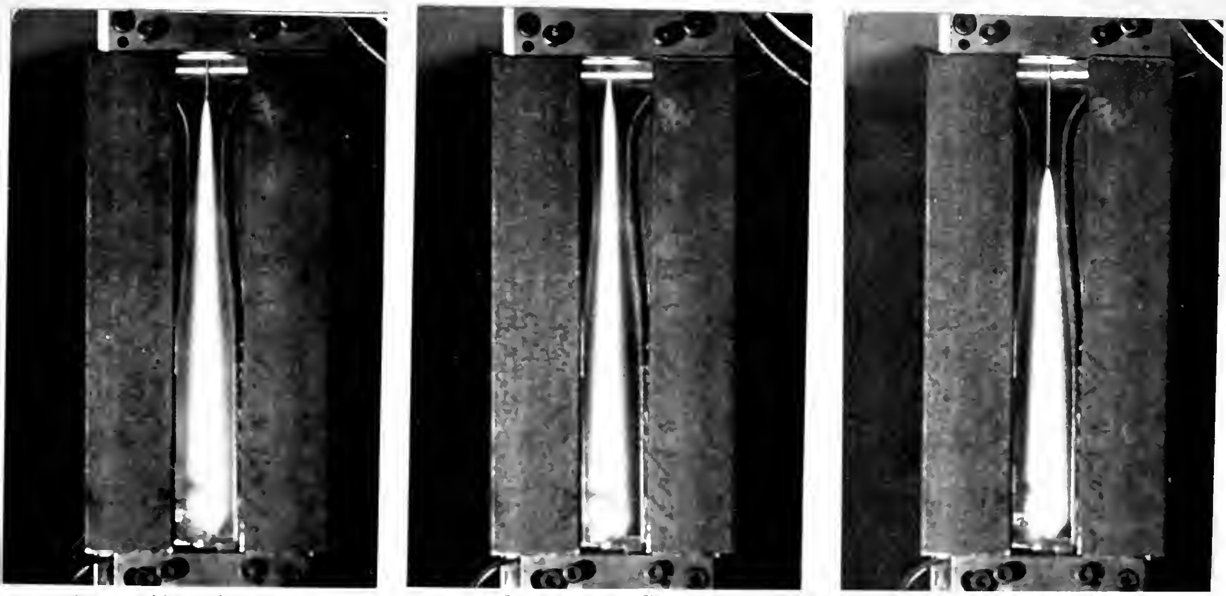


Figure III
Comparison of stagnation pressure ratio vs Water/Air ratio for various types of water injection.

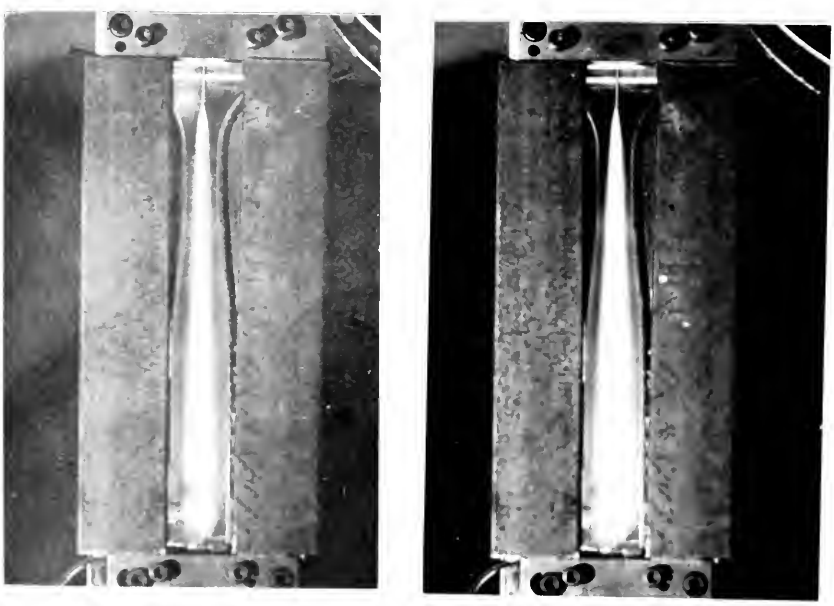
Figure IV. Dispersion of Injected Water



Near the Throat (Type A) | Before the Throat | After the Throat

Figure IVa. Axial types of water injection at the design rate

(0.14 pounds of water per pound of air.)



(1) (2)

Figure IVb. Type A injection at:
(1) Less than design rate
(2) Greater than design rate

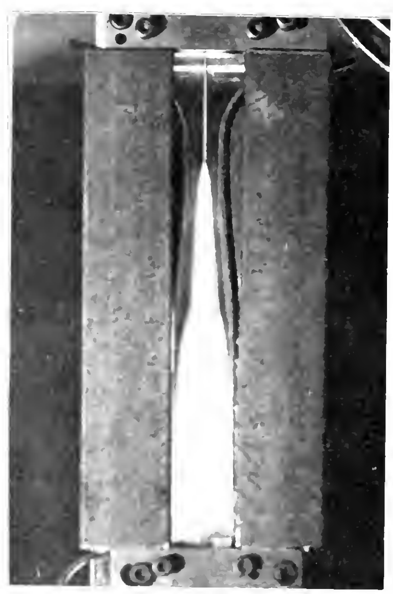


Figure IVc. Effect of Normal shock on the dispersion.

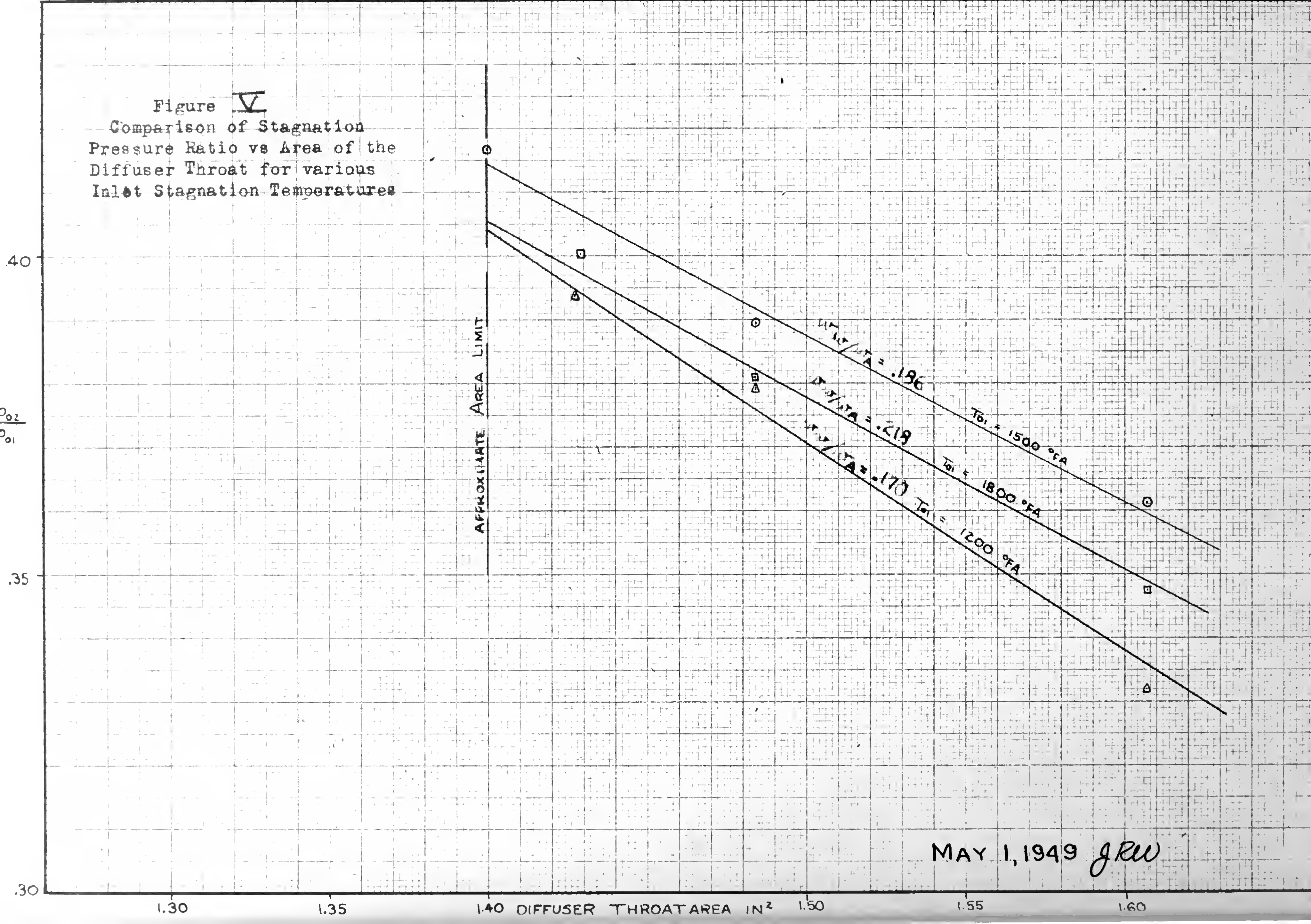


Figure V
Comparison of Stagnation Pressure Ratio vs Area of the Diffuser Throat for various Inlet Stagnation Temperatures

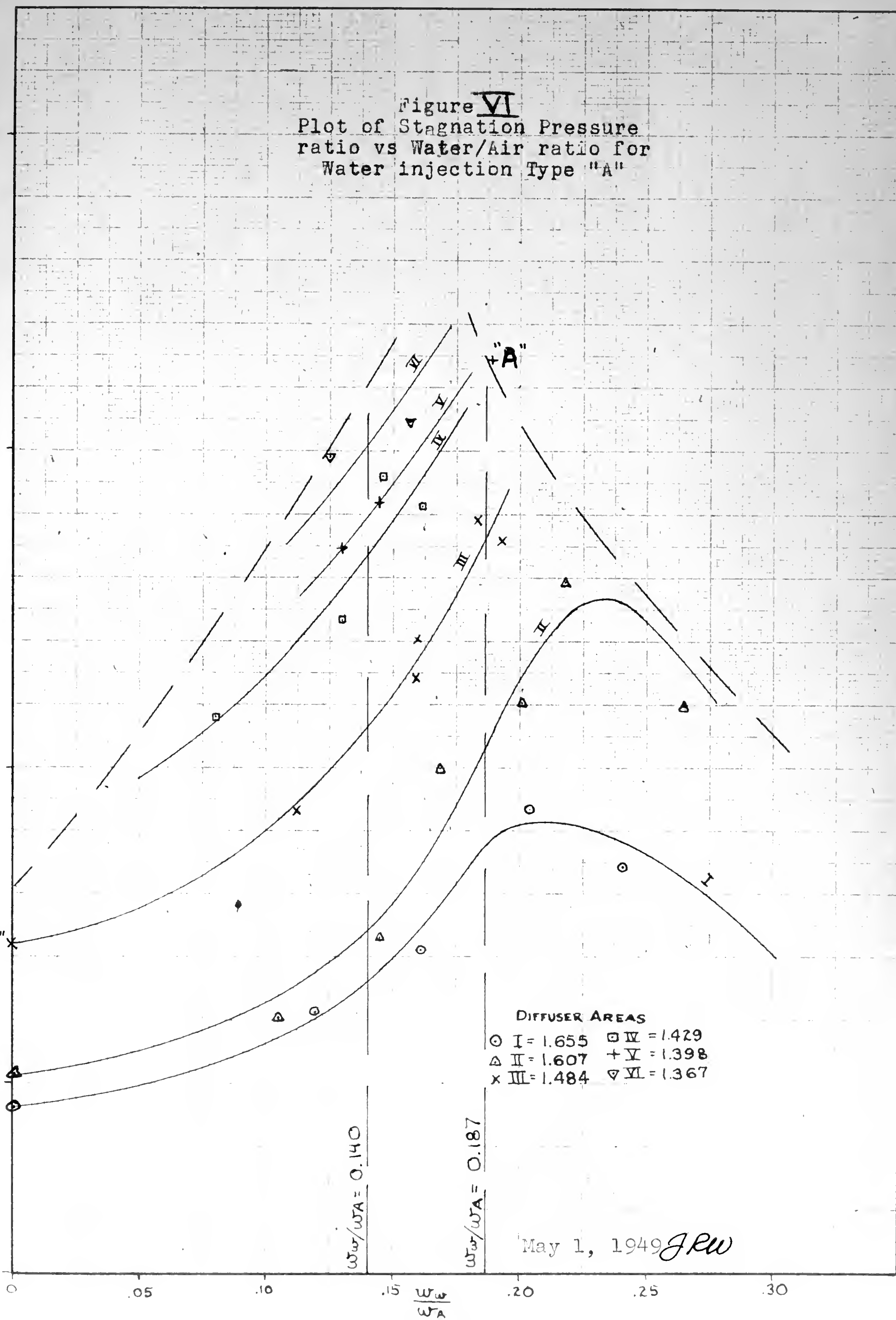


Figure VI
Plot of Stagnation Pressure ratio vs Water/Air ratio for Water injection Type "A"
.45
.40
.35
.30
.27
"A"
"B"
I
II
III
IV
V
VI
$\frac{p_{02}}{p_{01}}$
$\frac{w_w}{w_A}$
$w_w/w_A = 0.140$
$w_w/w_A = 0.187$
DIFFUSER AREAS
⊙ I = 1.655
△ II = 1.607
× III = 1.484
⊡ IV = 1.429
+ V = 1.398
▽ VI = 1.367
0
.05
.10
.15
.20
.25
.30
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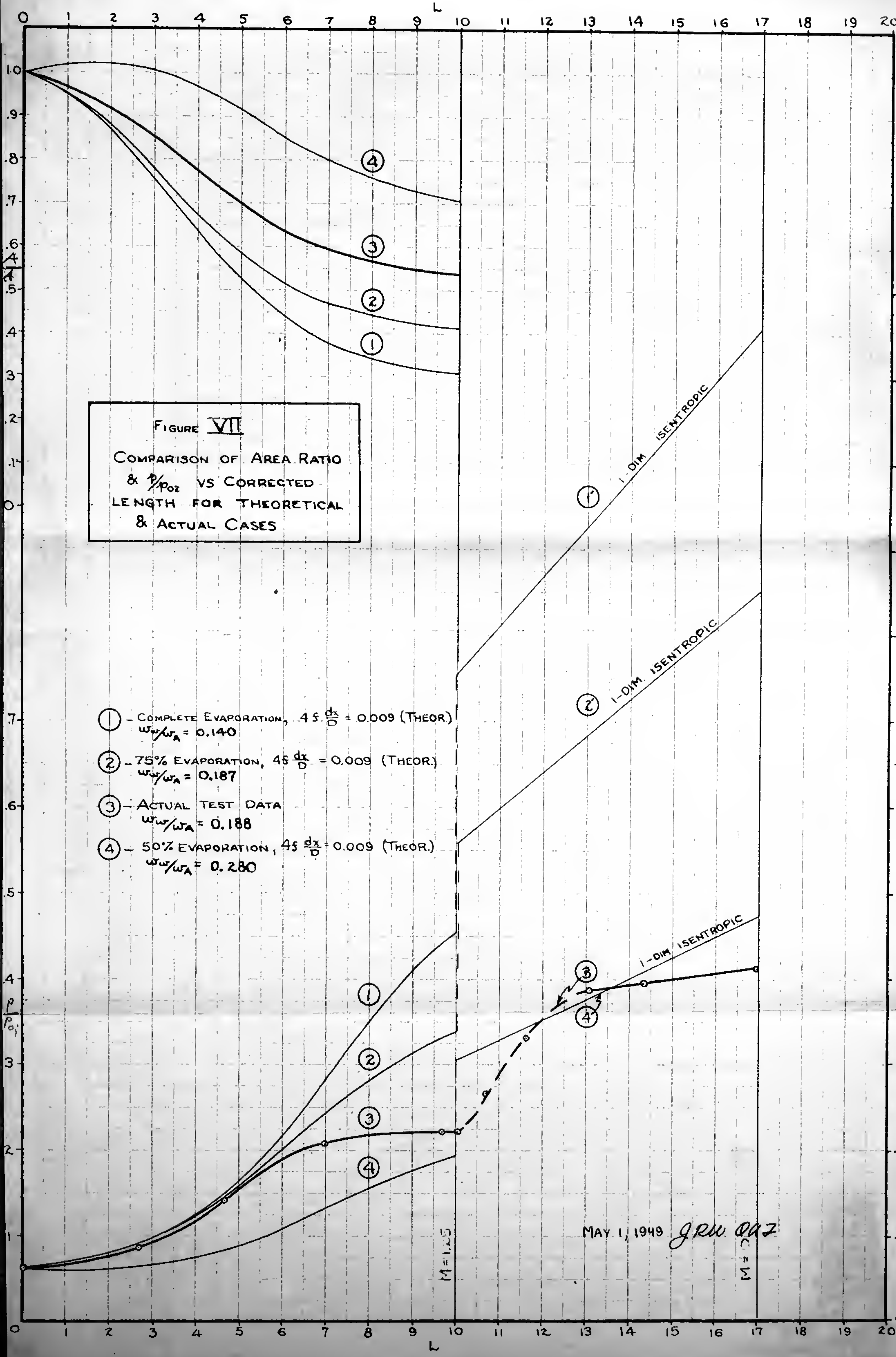

FIGURE VII
COMPARISON OF AREA RATIO & p/p$_{oz}$ VS CORRECTED LENGTH FOR THEORETICAL & ACTUAL CASES
(1) - COMPLETE EVAPORATION, 4f dx/D = 0.009 (THEOR.) w$_w$/w$_A$ = 0.140
(2) - 75% EVAPORATION, 4f dx/D = 0.009 (THEOR.) w$_w$/w$_A$ = 0.187
(3) - ACTUAL TEST DATA w$_w$/w$_A$ = 0.188
(4) - 50% EVAPORATION, 4f dx/D = 0.009 (THEOR.) w$_w$/w$_A$ = 0.280
1-DIM. ISENTROPIC
L
A/A
p/p$_{oi}$
M = 1.25
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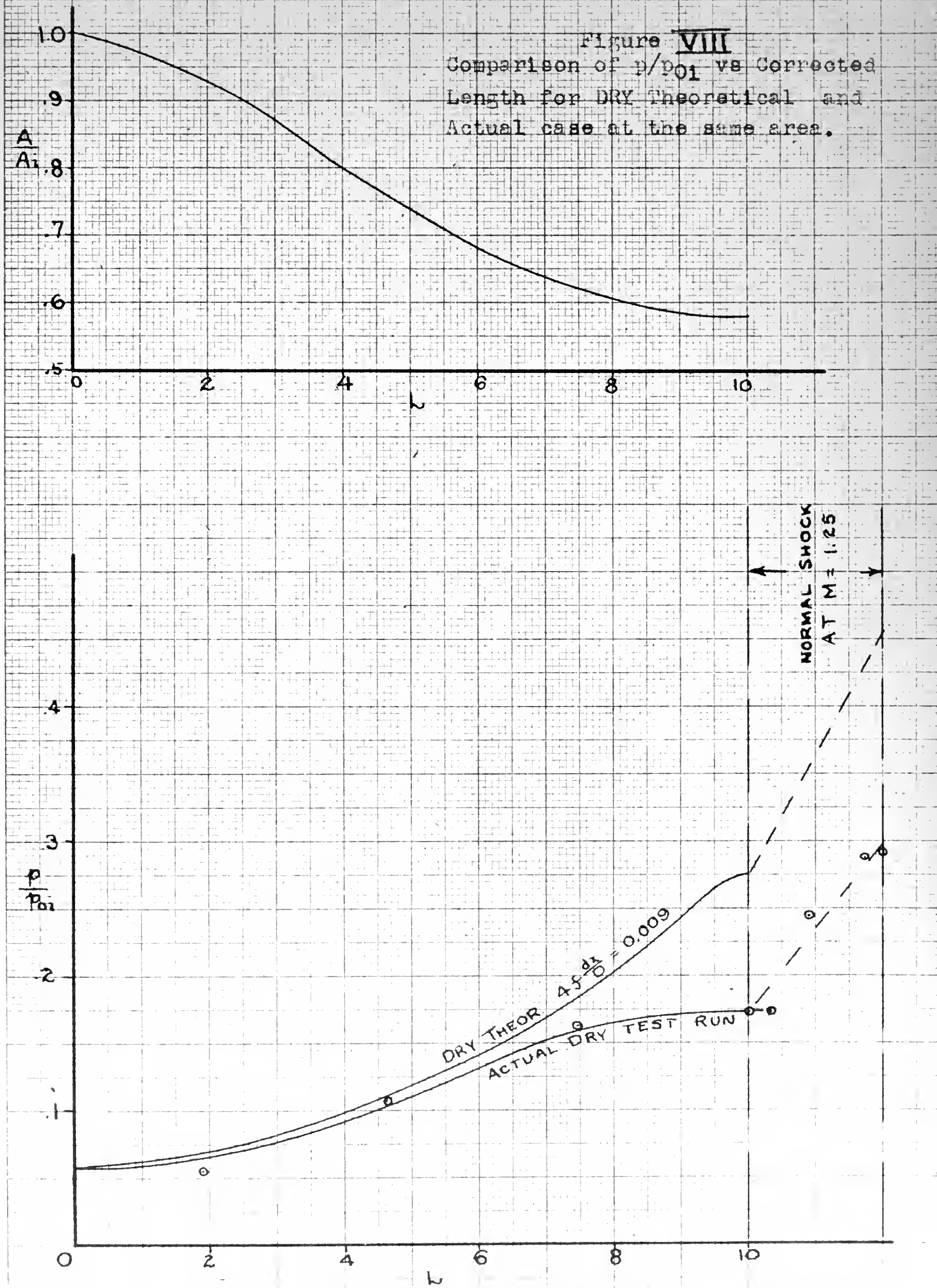
Figure VIII
Comparison of p/p_{01} vs Corrected Length for DRY Theoretical and Actual case at the same area.



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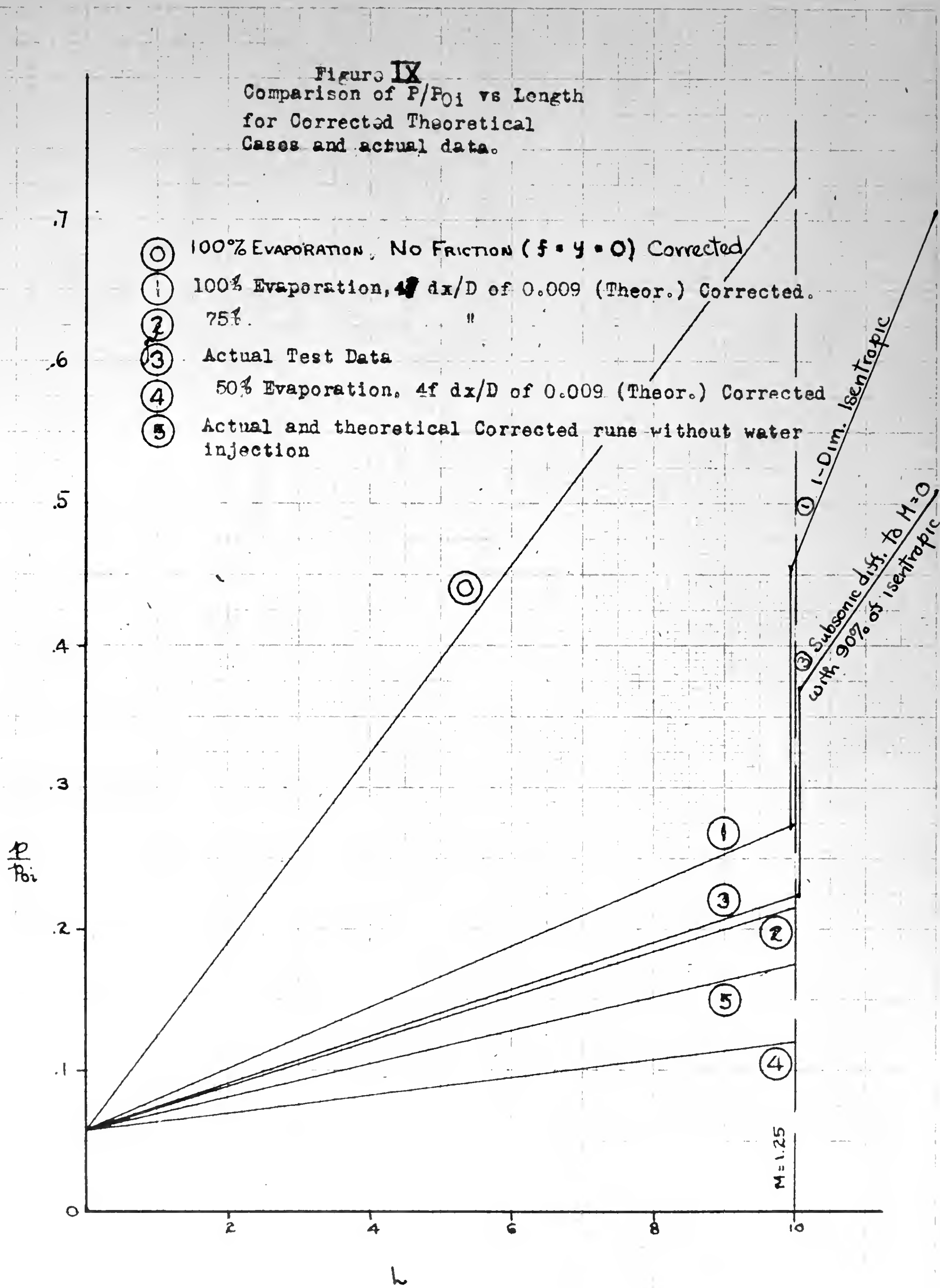

Figure IX
Comparison of P/P_{0i} vs Length for Corrected Theoretical Cases and actual data.

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V DISCUSSION OF RESULTS

This section is divided into the following discussions; the determination of the optimum operating conditions, the comparison of the theoretical and actual performance, and the possible improvements of the actual performance.

Optimum Operating Conditions

It was determined experimentally that the optimum operating conditions were obtained with a T_{01} of 1500 degrees FA, and with axial water injection ½" before nozzle throat (type A) at a rate of 0.188 pounds of water per pound of air. Consideration of figures III to VII explains why these conditions gave optimum results.

Figure III shows that type A was the best method of injecting water, since undesirable effects were less than for any of the other types. Two methods, types C and E, caused strong shocks in the supersonic gas stream, resulting in unstable operation for which complete data could not be obtained. This condition occurred on all attempts to introduce the water in the supersonic region of the gas stream, except for very low water rates. For the small apparatus used, the water stream introduced was appreciable in size compared to the gas stream, resulting in large disturbances to the supersonic flow. Type D injection could be used only at low water rates, for the reasons noted above.

Type B showed inferior results compared with type A, because the dispersion of the injected water in the gas stream was less complete, as shown in the photographs Figure IVa. This figure shows that the best dispersion of the liquid in the gas stream is obtained with the

injection at the nozzle throat. Type A best approximated this condition without disrupting the supersonic stream. However, even Type A produced a dispersion through only about 60% of the gas stream. Figure IV b shows that better dispersion results from higher flow rates. From considerations of all the factors involved, Type A proved to be the best method of injection, and was used for all subsequent tests.

Figure V shows that the best results were obtained at the design inlet stagnation temperature of 1500 degrees FA., however, the effect of inlet stagnation temperature over a range of temperature near the design point proved to be slight. Only a few tests were made at 1200 and 1800 degrees FA, since the performance at these temperatuses was so little different from that at the design point. Better results might have been obtained at 1800 degrees FA, but further investigation at this high temperature was prevented by the physical limitations of the apparatus. Thus it is shown that the designed inlet stagnation temperature of 1500 degrees FA was satisfactory as regards temperature.

Figure VI shows that the water injection rate for the highest stagnation pressure ratio attained was 0.168 pounds of water per pound of air with the smallest possible diffuser throat area. This water injection rate approximates the rate theoretically required for 75% evaporation. For the optimum water rate, the performance improves as the diffuser throat area is decreased. Thus the diffuser throat area attainable is a criterion of the performance of the apparatus. For the smaller diffuser throat areas, the range of water injection rates was restricted as shown by the limit lines. For

water injection rates outside of this range the flow was choked. Along these lines it was difficult to obtain data, since small variations of injection rate would cause choking. Therefore, the location of the limit lines is approximate. For small diffuser throat areas, a certain amount of pressure rise is necessary for the flow to continue without choking. At low rates of water injection the pressure rise derived from evaporation is insufficient to sustain the flow. At high rates of injection, the loss of stream stagnation pressure due to drag of the liquid more than offsets the effect of evaporation.

In figure VI, the curve for area I shows that a stagnation pressure ratio can be obtained with water injection that is 15.5% better than with no water injection at this area. Area I is the minimum diffuser throat area for which a supersonic flow can be started in the evaporation section with no water injection. Thus, this curve shows the improvement of a fixed-geometry diffuser by injecting water. The stagnation pressure ratios for operation as a variable area diffuser, points "A" and "B", show the best pressure ratio attained with and without water injection, respectively. The stagnation pressure ratio is 28.5% higher with water injection than without.

This improvement in performance can be realized in a supersonic wind tunnel, if the "Aero-Thermoprex" is used. The tunnel would consist of an air heater, the nozzle and the test section, followed by the evaporation section rather than a conventional supersonic diffuser. The pressure rise in the evaporation section would reduce the compressor power required.

Comparison of Theoretical and Actual Performance

Experimental results show a qualitative agreement with the predictions of the modified theoretical one-dimensional analysis. However, some material differences exist between the theoretical and the actual operation. These facts are shown in a consideration of the pressure and the area curves.

Figure VII shows that the area change achieved experimentally in the evaporation section, lies between the area change for 50% and for 75% evaporation for a theoretical constant-temperature process. The pressure obtained in the outlet of the evaporation section (diffuser throat), is only slightly better than the theoretical pressure for 50% evaporation, whereas the water injection rate was the same as the theoretical rate for 75% evaporation. Thus the actual evaporation apparently lies between 50% and 75% of the injected water. Since the water was not injected in increments along the evaporation section, but rather injected entirely at the inlet, it is probable that the evaporation rate was higher at the inlet than at the exit. Near the exit from the evaporation section, the shape of the actual pressure curve departs materially from the shape of the theoretical curves. However, this departure from the theoretical curves cannot be attributed wholly to poor evaporation

There is an important difference between the theoretical and actual processes, which can be seen from a consideration of figure VIII. The curves for figure VIII, which are obtained with no water injection, also show that the shape of the actual pressure curve differs from the

theoretical near the diffuser throat. The failure of the actual process to attain the pressure rise theoretically predicted must be due to losses not accounted for in the one-dimensional theory, since a reasonable friction factor was assumed in the theoretical calculations. The pressure rise obtained without water injection does not follow the theoretical, therefore, it is to be expected that with water evaporation the same types of losses would result.

In the evaporation section the supersonic stream is converging, which leads to oblique or normal shocks even when the diffuser throat is large enough to prevent choking. The strength of the oblique shocks depends on the boundary layer conditions and the angle of convergence of the stream, thus supersonic diffusion is a function of the geometry of the flow passage and not of the evaporation. Shocks always cause stagnation pressure losses. The losses associated with shock patterns were beyond the scope of the original analysis, but due to their magnitude, they should be considered in future investigations.

In figure IX the theoretical curves are arbitrarily corrected to account for these losses, in order to compare the theoretical and actual cases on a realistic basis. The figure indicates that about 75% of the injected water is evaporated. The end point of Curve 1, P/P_{0i} of 0.655, in figure IX, shows the highest stagnation pressure ratio which can theoretically be attained on the apparatus tested. It may be noted that if the apparatus tested were provided with a subsonic diffuser of good efficiency, about 90% of the isentropic stagnation pressure at the diffuser throat would be recovered and a

stagnation pressure ratio of 0.51 would be attained.

Possible Improvements of the Actual Performance

Without increasing the size of the apparatus tested, the performance could be materially improved in several ways. 1) The method of water injection could be altered so that with type A injection, several water injection tubes could be used. This would permit more complete coverage of the gas stream and higher injection velocity, thus decreasing the drag of the liquid stream. 2) The converging evaporation section passage could be designed taking into account oblique shocks to lessen their effect. 3) The subsonic diffuser, which diverges too rapidly, could be designed for a much better efficiency. These improvements would make the actual performance approach Curve 1 of figure IX.

The absolute size of the "Aero-Thermoprex" may have an appreciable effect on the stagnation pressure rise obtainable. This manifests itself in several ways, which tend to counteract the sources of deviation from theoretical results. These sources are; the effect of friction, the lack of complete evaporation, and the loss of stagnation pressure in a converging passage by oblique pressure shocks. The effect of size on the last of these is problematical. Presumably, they are produced by the geometry of the passage only, and would be unchanged if all dimensions were increased in the same ratio. However, the formation of pressure shocks is intimately tied up with boundary layer phenomena, which are decidedly affected by size. The net effect is not predictable. It is felt that in a larger apparatus, the rate

of evaporation could be made to approach the theoretical rate, due to two causes; the length available for evaporation increases, and the mechanical difficulties of stepwise water injection are decreased. As shown by the tests, the failure of peripheral injection was due to the creation of shocks by the normal injection of a water stream which was large relative to the flow passage. Smaller injection holes were impractical due to the manufacturing and operating difficulties. With a larger flow passage the same size holes would be no longer large enough relative to the stream, to create shock disturbances. Furthermore, the number of injection steps could be increased with the size of the machine and could be more closely controlled. The effect on friction is readily apparent. As the equivalent diameter is made large for a given length, the term $4f\ dx/D$ can be made very small and friction becomes less important. However, there is an important secondary effect here which must be recognized. Since, for a given process, the area ratios remain constant per unit of length of evaporation, if D is increased with constant length, the angle of convergence of the passage becomes greater. This will have an effect on the stagnation pressure losses due to shock associated with converging a supersonic stream. The magnitude of this effect is not known. Within certain limits of convergence angles, however, it has been shown to be small. If the increase in diameter can be accomplished without exceeding these limits, a real gain can be realized in diminishing the harmful effects of friction. One more factor is influenced by absolute size. As pointed out above, the same size injection holes can be retained with the larger apparatus. Since the amount of water injected increases with

size, higher injection velocities may be obtained, thus giving the injected water the highest possible forward momentum.

While it is evident that no qualitative result can be deduced from the foregoing discussion, it appears that material gain can be secured by increasing the gross size of the "Aero-Thermoprex".

VI CONCLUSIONS AND RECOMMENDATIONS

1. The stagnation pressure ratio, P_{02}/P_{01}, obtained with water injection is 28.5% better than with no water injection. This improvement in performance could be used to advantage in supersonic wind tunnels.
2. The evaporation of the injected water experimentally obtained is about 75% complete.
3. The experimental results partially substantiate the results predicted by a theoretical one-dimensional analysis, where friction effects were included.
4. Oblique shock and boundary layer phenomena not included in the analysis are important in the supersonic diffusion of the stream and cannot be neglected.
5. The performance of the experimental apparatus can be improved by:
    a. Using a battery of smaller axial injection tubes to give more complete dispersion through the stream, and higher water injection velocities.
    b. Designing a good variable area supersonic and subsonic diffuser, considering oblique shock and boundary layer phenomena.
6. The performance of a full size apparatus can be made better than that of an experimental model. The water injection and evaporation and the supersonic diffusion could be improved, and the friction losses decreased.

VII. APPENDIX

A P P E N D I X "A"

DATA FROM TESTS

INLET TEMP. ABOUT 1500°FA

May 1, 1949 JRW

DIFF. THR'T. AREA	1.837 in²			I · 1.655 in²					II · 1.607 in²			
RUN NO.	35	7	53	75*	76*	77*	78*	79*	36	11	14	15*
T_{01} °FA	1508	1483	1497	1513	1509	1495	1508	1513	1509	1486	1509	1509
T_{02} °FA	1170	836	810	1100	840	710	578	575	1180	759	770	770
p_{01} Cm Hg	76.3	76.2	76.2	75.8	75.8	75.8	75.8	75.8	76.2	76.2	75.1	75.1
p_{02} Cm Hg	18.8	19.8	23.0	22.5	23.6	24.4	26.1	25.4	23.0	22.6	21.3	23.1
WATER RATE LB/HR.	DRY	60	75	DRY	75	100	128	150	DRY	80	80	80
TYPE OF INJ.	—	B	E	—	A	A	A	A	—	B	B	B
REMARKS				MIN. DRY START. AREA								

DIFF. THR'T. AREA	II = 1.607 in²											
RUN NO.	16	18	20	22	24	25	29	39	43	45*	47*	51*
T_{01} °FA	1497	1494	1533	1523	1519	1515	1515	1507	1515	1509	1509	1509
T_{02} °FA	713	570	645	730	643	665	760	800	815	843	735	576
p_{01} Cm Hg	75.1	75.1	75.1	75.1	75.1	75.1	75.1	76.2	76.1	76.2	76.2	76.2
p_{02} Cm Hg	23.4	22.7	23.1	22.1	23.6	22.0	21.7	23.5	23.6	23.7	24.7	29.0
WATER RATE lb/hr	105	120	95	75	80	90	80	77	80	65	90	135
TYPE OF INJ.	B	B	C	C	A	A	A	A	A	A	A	A
REMARKS												

DIFF. THR'T. AREA		II = 1.607 in²									1.510 in²
RUN NO.	64*	67*	69*	71*	73*	84*	58*	60*	62*	54*	55*
T_{01} °FA	1513	1512	1250	1250	1240	1803	1512	1508	1509	1508	1508
T_{02} °FA	608	580	643	564	565	665	570	574	740	810	810
p_{01} Cm Hg	74.85	74.95	74.95	74.95	74.95	75.7	76.2	76.2	76.2	76.2	76.2
p_{02} Cm Hg	26.25	27.15	24.45	24.85	27.15	26.3	27.5	27.7	25.2	25.4	26.6
WAT. RATE lb/hr	105	125	80	105	115	135	165	130	80	75	75
TYPE OF INJ.	A	A	A	A	A	A	D	D	D	E	E
REMARKS			NOTE $T_{01} \cong$ 1200°FA			NOTE T_{01} 1800°FA					

NOTE: * INDICATES BACK PRESSURE RAISED AS HIGH AS POSSIBLE.

TYPE OF INJECTION: (A) AXIAL INJ. ½" BEFORE NOZZLE THR'T.
(B) " 1" "
(C) " AT NOZZLE THR'T.
(D) LAST 2 SIDE BLOCKS + AXIAL INJ. ½" BEFORE NOZZLE THR'T.
(E) SIDE BLOCKS ONLY.

TEST DATA

May 1, 1949 JRW

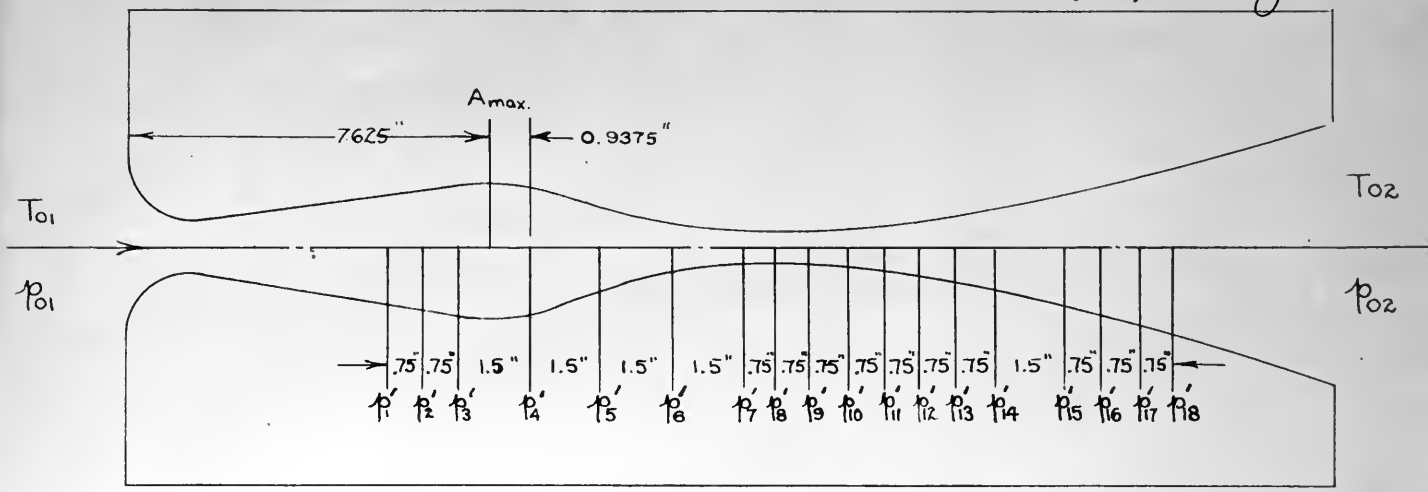
DIFF THR'T. AREA	III = 1.484 in²											
RUN NO.	37	12	17	19*	21	26	40	44*	46*	48*	52*	65*
T_{01} °FA	1509	1493	1495	1498	1510	1515	1509	1490	1509	1511	1509	1513
T_{02} °FA	1183	756	723	600	653	670	771	810	843	725	575	580
P_{01} Cm Hg	76.2	76.2	75.1	75.1	75.1	75.1	76.2	76.2	76.2	76.2	76.2	74.85
P_{02} Cm Hg	24.6	26.6	26.1	27.2	26.7	25.1	25.0	26.2	23.7	27.8	29.7	27.75
WAT. RATE lb/hr	DRY	79	90	120	95	90	77	70	65	100	115	100
TYPE OF INJ.	—	B	B	B	C	A	A	A	A	A	A	A
REMARKS												

DIFF. THR'T. AREA	III = 1.484 in²								IV = 1.429 in²			
RUN NO.	68*	70*	72*	83*	57*	59*	61*	63*	38	13*	27	31*
T_{01} °FA	1509	1255	1250	1803	1512	1509	1509	1509	1508	1443	1516	1509
T_{02} °FA	579	675	563	665	570	563	740	740	1193	770	680	770
P_{01} Cm Hg	74.95	74.95	74.95	75.7	76.2	76.2	76.2	76.2	76.2	76.2	75.1	75.1
P_{02} Cm Hg	28.95	27.35	28.25	27.7	28.2	29.4	29.7	29.3	27.1	29.4	27.4	28.2
WAT. RATE lb/hr	120	84	105	135	108	165	80	80	45	72	90	80
TYPE OF INJ.	A	A	A	A	D	D	D	D	—	B	A	A
REMARKS		NOTE $T_{01} \cong$ 1250 °FA		NOTE $T_{02} \cong$ 1800								

DIFF. THR'T. AREA	IV = 1.429 in²					V 1.398 in²		V 1.398 in²		1.382	VI 1.367 in²	
RUN NO.	41	49	50*	66*	85*	28*	32*	81	80*	33*	82*	42*
T_{01} °FA	1507	1509	1509	1509	1790	1486	1533	1496	1493	1533	1496	1507
T_{02} °FA	800	720	705	580	665	660	780	558	558	796	680	800
P_{01} Cm Hg	76.2	76.2	76.2	74.85	75.7	75.1	75.1	75.7	75.8	75.1	75.7	76.2
P_{02} Cm Hg	27.9	29.4	30.3	29.35	30.3	29.5	29.0	27.9	31.6	29.4	30.8	30.6
WAT. RATE lb/hr	77	90	90	100	135	90	80	115	115	80	98	77
TYPE OF INJ.	A	A	A	A	A	A	A	A	A	A	A	A
REMARKS					NOTE $T_{02} \cong$ 1800							

Complete Test Data For Typical Runs

May 1, 1949 JRW



Run No.	38	37	75	82	68	80	78
Diff. Thr't Area	1.429	1.484	1.655	1.367	1.484	1.398	1.655
T_{01} °FA.	1508	1509	1513	1496	1509	1493	1508
T_{02}	1193	1190	1100	680	579	558	578
Water Rate	45	Dry	Dry	98	120	115	128
p_1' Cm Hg	6.0	6.1	6.1	6.7	6.5	6.8	6.7
p_2'	5.1	5.2	5.3	5.8	5.7	5.9	5.8
p_3'	4.4	4.4	4.5	4.9	4.8	5.0	5.0
p_4'	3.7	3.7	3.7	4.0	4.0	3.9	4.1
p_5'	8.7	8.2	8.4	10.3	10.7	10.8	11.0
p_6'	13.9	12.5	10.5	15.2	15.5	15.8	12.5
p_7'	13.4	13.1	13.7	17.8	14.7	16.4	15.7
p_8'	15.8	13.7	17.2		21.4	20.1	21.9
p_9'	20.2	18.6	20.2		23.2	24.4	23.0
p_{10}'	23.8	21.9	21.0		24.4	27.4	24.0
p_{11}'	24.7	22.6	21.5		24.9	28.5	24.4
p_{12}'	25.6	23.4	21.6		25.9	29.5	24.8
p_{13}'	26.0	23.5	21.8		26.1	29.5	24.9
p_{14}'	26.2	23.7	21.9		26.4	29.6	25.2
p_{15}'	26.2	23.8	21.9		26.6	29.8	25.4
p_{16}'	26.5	24.0	—		26.6	—	—
p_{17}'	26.6	24.1	—		26.8	—	—
p_{18}'	26.8	24.3	—			—	—
p_{01}	76.1	76.1	75.7	75.7	74.95	75.8	75.8
p_{02}	27.1	24.6	22.5	30.8	27.95	31.6	26.1

A P P E N D I X "B"

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